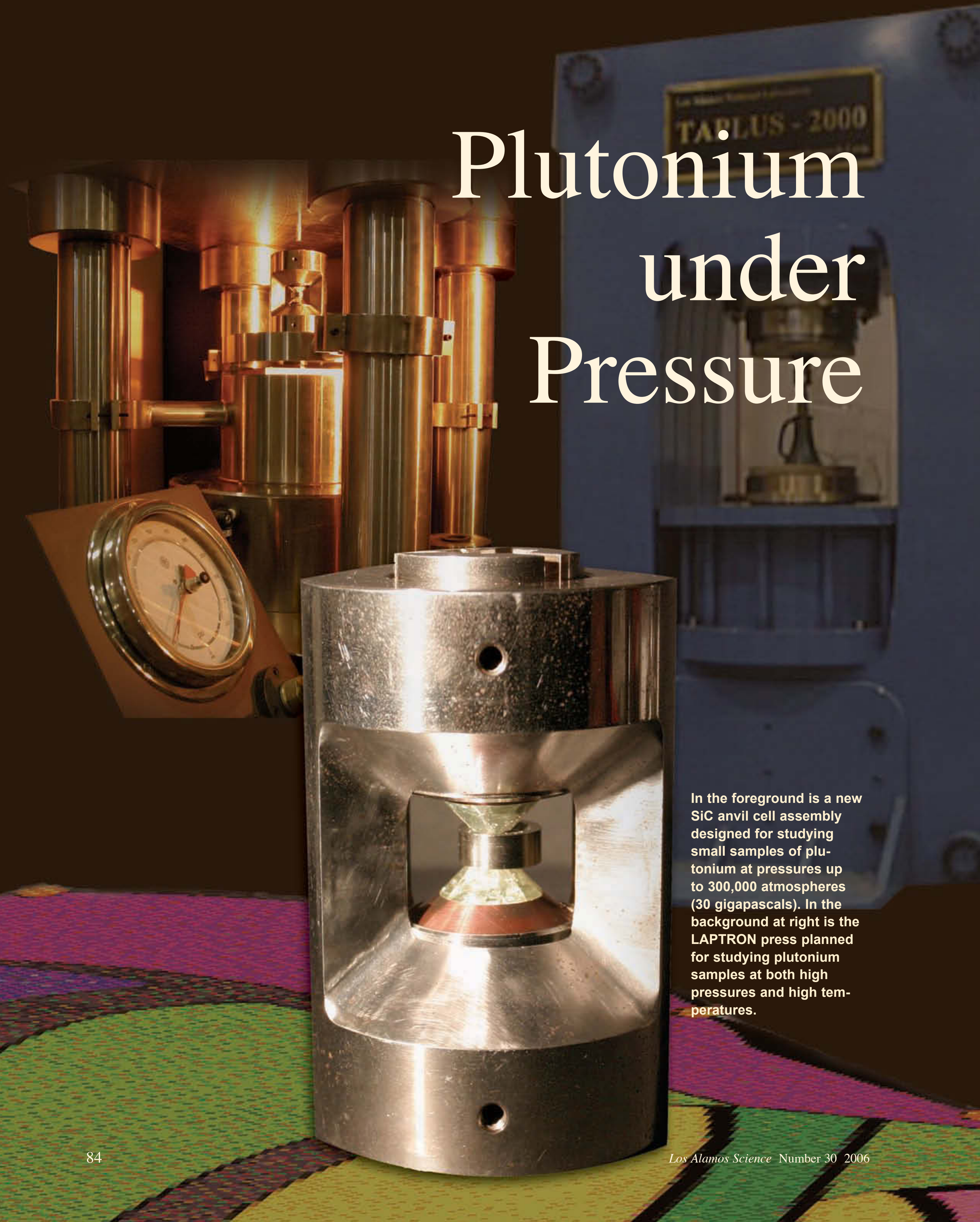
Plutonium under Pressure



In the foreground is a new SiC anvil cell assembly designed for studying small samples of plutonium at pressures up to 300,000 atmospheres (30 gigapascals). In the background at right is the LAPTRON press planned for studying plutonium samples at both high pressures and high temperatures.

Introduction

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It is a coincidence that the nuclei of plutonium-239, whose fission properties were predicted before they were used in the atomic bomb, have electrons around it with collective properties that have made this metal difficult to work with for over sixty years. There is no reason that a useful nucleus should be surrounded by badly behaving electrons. As the atomic number—that is, the electric charge on the atomic nucleus—increases, electrons must be added to the electron shells surrounding these nuclei to maintain charge neutrality. The organization and energies of the electrons when the atoms condense into a crystalline form are determined by the rules of quantum mechanics, but unlike nuclear properties, most material properties are too complicated to be predicted directly from quantum mechanics. Among the complications are the occurrence of many different phases and the effects of impurities.

Steel is a difficult material to process because its phase diagram with carbon and other low-level constituents is so complex. But this variety in behavior has a big payoff in allowing us to adjust its strength and properties to the needs of society. Plutonium is also one of the most difficult materials to process and predict for much the same reasons as steel. In both metals, the fact that magnetism can appear or be absent depending on the arrangement of atoms and their spacing leads to the astounding richness of properties. Steel is usually magnetic, and plutonium is not. They are on opposite sides on the divider between magnetism and non-magnetism, but their complex properties depend on the two metals being close to this crossover. The properties change because, if some electrons contribute to magnetism, they do not participate in holding the metal together. Seemingly insignificant differences in pressure, impurities, processing, and environment lead to major changes in behavior. It takes all of today's best theories, calculations, and experiments even to begin to understand what is going on and to attempt to predict properties more accurately.

At Los Alamos and Lawrence Livermore National Laboratories, a new generation of scientists has joined forces with the veterans in this field and is beginning to produce answers. For the Stockpile Stewardship Program we need to know what plutonium does at all temperatures, pressures, and long times to have some ability to predict the behavior of plutonium outside of what we can measure in laboratory experiments. The new generation has shown that radiation damage in plutonium at low temperatures gives rise to magnetism, and this tendency for electrons to localize around defects affects mechanical properties even at room temperature. The radiation damage experiments have also led to a promising idea for understanding why, under ordinary conditions, plutonium often occurs in two forms—alpha and delta—with very different properties.

As discussed in the two short articles that follow, the delta form seems to consist of two different quantum phases, a quantum analog of the mixture of water droplets and water vapor that occurs when it rains. The article by Angus Lawson suggests that the phase coexistence in delta plutonium can explain its negative thermal expansion. The article by Albert Migliori shows that the effects of negative thermal expansion on compressibility are not easily explained by single-phase theories. More recently, it has been conjectured that this same kind of phase coexistence may describe the organization of electrons in a solid when they are on the verge of magnetism.

We also need to visualize how the atoms move when the structure changes. Better plutonium samples are needed to understand how radiation damage and impurities come into play, or equivalently, what the starting material really is. It is clear that the study of plutonium will be important for fundamental research and, equally so, for the weapons program for years to come. The new scientists do worry, however, that the increasing bureaucracy of handling plutonium, which is more based on fear than safety, confounds their futures.